Subsurface Fracture Characterization based on Polarimetric Borehole Radar and its Application to Estimation of Hydraulic Properties

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論文内容要旨

Subsurface fracture characterization is related to various applications and it is not an easy task to determine. The full polarimetric borehole radar system can obtain that goal. In this dissertation, the radar polarimetric analysis was used to provide the physical properties of subsurface fractures. These results in addition introduce a new connection for hydraulic studies of fractures. The verification for using this polarimetric analysis was confirmed by implementing EM forward simulation of determined fracture models.

In the first part of the thesis, the configuration of the polarimetirc borehole radar was described. The measuring of the full polarimetric data set can be derived with combining the dipole and slot antennas, which can radiate and receive co-polarized and cross-polarized electromagnetic waves. Using the full polarimetric radar system, the single-hole measurements were done at two test sites, first one is at Kimaishi site, Japan, and the other is at the Mirror Lake in Grafton County, New Hampshire, USA. The polarimertic analysis of the measured data at Mirror Lake site was used because it contains the hydraulic tracer tests that can be correlated with the obtained polarimetric results.

The fractures were modeled based on the fractal concept as it represents one of the closest approaches for modeling the real fractures. Two factors can various the fracture roughness which are proportional constant parameter (C) and the fractal dimension.

The variation of the fracture surface heights was adjusted with the proportional constant parameter (C) only. Since it preserve the correlation length of the generated fracture to be the same and the changeable parameter is the RMS height.

FDTD method was implemented for the numerical experiments in this thesis. The EM backscattered was observed for different rough fractures. The full polarimetric FDTD simulation data have been calculated for different rough fracture models and the validation of the measured data and its mean power scattering matrix analysis for FSE1 borehole has been done. The full polarimetric backscattered wave shows proportional change in amplitude of cross-polarization (VH and HV) components depending on the fracture roughness. Using mean power scattering matrix of the simulated results revealed that the full polarimetric borehole radar dataset can estimate the subsurface fracture characteristics.

The polarimetric analysis based on the three eigenvector parameters, entropy, anisotropy and alpha was used. The verification of using the three polarimetirc parameters for fracture characterization has been shown by using EM forward modeling of different synthesized fracture models. The three polarimertic parameters revealed various distribution patterns with changing of the fracture roughness property. EM simulation results emphasized, the anisotropy parameter provides complementary information to the entropy and facilitates the interpretation of the scattering from rough fractures. Subsurface fracture characterization of the measured polarimetric borehole radar dataset has been shown based on the polarimetric analysis of the three eigenvector parameters. The polarimetirc analysis was estimated based on the single frequency datasets constructed at 30MHz. The correlation between our conclusions of subsurface fractures characterization and hydraulic tracer test results that were measured by USGS showed very good consistency. The full polarimetric borehole radar system can share with a big role for providing a lot of information related to the flow of water and its hydraulic property in fractured rocks.

Chapter 6 addresses the contribution of subsurface facture zones in hydrological situation of the groundwater aquifers in Egypt at Aswan area. The fracture zones, accompanied with fault systems, contribute toward recharging of the groundwater aquifers

either from the surface water (such as Lake Nasser) or internal water flow between the Nubian bearing formations. These results previewed in this chapter initiated a further investigation of how far the water of the Nile River is recharging the aquifers adjacent to its sides, especially for near zones from the River Nile course, and up to which extent this takes place. The proposed research has two important aspects in the context for Egypt. First, the extension of cities and villages around the river Nile is toward the west and east sides of the Nile banks and it will mostly depend on the groundwater resource for irrigation and drinking. Second, we can monitor the amount of infiltrated water from the Lake Nasser into subsurface aquifers and forecast the amount that annually can recharge into the Nubian aquifer. As, this process affects the quality of groundwater as well as we may determine the expected horizontal development of a new urban societies depending on the usage of groundwater in these locations.

The fracture properties of the basement rock and the overlain Nubian sandstone at southwest Aswan area have been shown based on the surface exposed rock units and the cored samples. The fractures have formed in that region due to tectonic actions, the weight pressure of water of Lake Nasser and physical erosion due to so heavy rain in the Holocene age. It was found at southwest Aswan area that fracture zones have different widths as in some cases it be 3 to 4 cm in the basement complex and up to 30cm for the Nubian Karst sandstone feature. The implementation of FDTD modeling for the observed fracture parameters at Aswan area can be used for defining their hydraulic characteristic related to the polarimertic analysis with referring to the obtained results of Mirror Lake fracture test site.

The full polarimetric borehole radar system in this research, with integration of surface geophysical measurements (geoelectric, electromagnetic, geomagnetic and seismic), can differentiate the fracture zones in subsurface for several characterized fracture sets as in crystalline, limestone and sandstone rock types. Thus, the similar fracture zones or sets can be formed due to the same tectonic process and they may end up having similar hydraulic property. The advantage of the polarimetric borehole radar system as subsurface sensing tool

is that it characterizes the whole fracture sets within the measured depths inside the borehole while it cannot be obtained from surface geophysical measurements and also may not be easily determined with other well logging methods. Finally, it is a cost effective method in contrast with other hydraulic borehole tests. In addition, it can be an alternative technique for obtaining different subsurface fracture hydraulic characteristics

Further applications are still can be done with the full polarimetric borehole radar such as exploring a new groundwater resources in arid regions and countries such as Egypt, Saudi Arabia, Kuwait and Libya that the groundwater accumulations are mainly found in fracture crystalline rocks and limestone.

論文審査結果の要旨

本研究はボアホーレーダを利用して地下き裂の性状評価を行うための基礎に関するものである。硬岩体中で地下水流動を支配するのは地下き裂であり、人工的な地下利用、地下貯蔵などでは地下環境への影響評価という観点から地下き裂の性状評価は重要な工学的課題である。

従来、地下水理特性はポンピングテストなど直接的な計測による評価が主体であったが、地中レーダは地下き裂の形状を非破壊的に可視化できる手法である。地下き裂の透水性が性状評価では重要であるため、地中レーダ計測と透水性の間の関係を明確にする必要がある。従来の研究で、き裂の表面粗さや破砕帯に含まれる岩石の粒径などが、透水性と強く関連するという報告がある。そこで、物質表面の粗さを計測するために、電波散乱の偏波状態を利用する、ポーラリメトリック・ボアホールレーダを利用した計測手法について本研究では論じている。

第１章は研究の背景である。

第２章では既存のボアホールレーダ技術、特に偏波計測に関してのシステム紹介と、既存のフィールド実験結果をまとめている。

第３章では、電磁界シミュレータを利用して電磁波反射・散乱解析を行うための地下き裂モデルの生成について論じている。本論文では、これまでの地下き裂観測例に立脚し、き裂表面形状をフラクタルモデルで形成することとし、そのシミュレーション手法について論じている。

第４章では生成したモデルを用いて、電磁波の散乱を FDTD（有限差分・時間領域）法によって行い、地下き裂モデルの形状パラメータと電波散乱の関係に関して詳しく論じた。

第５章では衛星リモートセンシングにおけるレーダポーラリメトリの分野で標準的な解析手法である固有値解析手法をボアホールレーダに利用し、エントロピー、異方性、平均傾斜角などのパラメータとき裂モデルの形状パラメータの関係について論じている。次に本手法を計測データに適用し、き裂形状パラメータとの関連づけを試みた。この結果、電波で計測したパラメータが、現地でのポンピングテストで明らかになったき裂透水性との明らかな関連を見いだすことに成功した。

第６章では提出者が実務として関わってきたエジプト・アスワン地域で観察される地下き裂の形態や物理的な性質についてまとめを行い、本研究で開発した地下き裂計測手法が透水性評価に利用可能であるという予察を行った。

第７章はまとめである。

エジプトでは、地熱発電に利用するため地下熱水系の調査が計画されている。本論文で得られた知見は地熱にとどまらず地球環境にかかわるさまざまな分野で、有用な計測手法を提供するものである。

よって，本論文は博士(　学術　)の学位論文として合格と認める。